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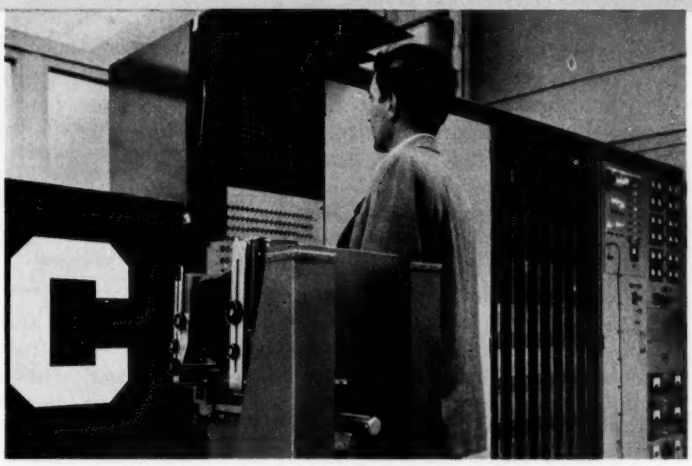
The MARK I PERCEPTRON

by JOHN C. HAY and
CHARLES W. WIGHTMAN†



Author John Hay observes letter shown to the Mark I's photo electric "eye" register on its stimulus monitor.

THE perceptron is an experimental machine, conceived by Dr. Frank Rosenblatt of the Cornell Aeronautical Laboratory, capable of performing some cognitive functions heretofore associated only with men or animals. One such task of which the Mark I perceptron is capable is the identification of optical patterns.

How Patterns are Identified

A basic pattern identification task might be performed by a machine in several ways. For example: suppose all those optical images that have the shape of a letter X are to be isolated. The simplest initial step would be to put a bank of photocells, or sensory units, into the image plane: this "retina" would then convert each optical image into an electrical activity pattern. To perform the X-identification task, it would be sufficent to construct a gating system* which passed only those electrical patterns which originated in an exactly X-shaped set of photocells.

Such a system would depend for its ability entirely on the precise image analysis and network design of an engineer, and it could not be used at other times for other identification tasks. On the other hand, a versatile system, which could perform many identification tasks, and which would furthermore *adapt* itself to each such task without structural modification, might be constructed. As many gating elements could be introduced in parallel as there are possible electrical activity patterns, and each gate could be allowed to pass a unique pattern signal. Thus every image would send a signal ultimately along a unique path in the network, and identifications for each image could be stored in those paths.

Such a system could be *trained* to perform an identification task by showing it, one at a time, each of the optical images involved. Simultaneously with each image presentation, an identification signal would be fed back and stored in the unique active path.

When the performance and structure of the latter "unique path" image identifier is compared with the performance and structure of biological image identifiers (men or animals) certain differences appear. These differences are striking both to those interested in automatizing surveillance tasks, and to those interested in biological systems. Dr. Rosenblatt noted especially the following behavioral and structural differences:[1]

1. A man ordinarily does not need to be trained on all possible X-shaped images in order to be able to identify all such images: i.e., it is characteristic of biological systems that they may apply the results of past experience to novel cases.
2. Several different kinds of anatomical and physiological evidence argue against the existence of unique paths in biological nerve nets for different patterns of input (e.g., the non-specific effects of tissue removal).
3. The size of the central networks of biological nervous systems is so large that highly detailed constraints on their fine structure seem unlikely.

Novel Network Suggested

These and other considerations suggested to Dr. Rosenblatt a novel kind of network. In this network there would be a number of parallel gates, but the

†This article is based on a paper presented by the authors last March at the I.R.E. National Convention in New York.

*A gate is defined as a circuit having an output and a multiplicity of inputs so designed that the output is energized when and only when a certain definite set of input conditions is met.

number could be far fewer than the number of possible optical images. Each gate could be passed by a number of different image signals and conversely, each image could have its signal passed* by a number of gates. Suppose, for example, that the gates were constructed at random. One would then expect that certain gates would be passed more often by the signals of X-shaped images than by those of non-X images.

Suppose now that during a training procedure (of the type mentioned above) a random but not exhaustive sample of X and non-X images is presented to the perceptron. As before, an identification signal is fed to the gates which pass an image signal. More specifically, suppose we feed a +1 when the image is an X, and a −1 when it is a non-X. Now let the gates add the identification signals they receive during the entire procedure. At the end of the training procedure, each gate would have a *value* equal to the difference between the number of times it had passed X signals and the number of times it had passed non-X signals.

EDITOR'S NOTE

Research on the Laboratory's perceptron program has been sponsored since July 1957 by the Office of Naval Research with the assistance since 1958 of the Rome Air Development Center of the Air Research and Development Command.

The value which a gate acquires during such a training program can be regarded as an estimate of the likelihood that an image signal which passes it comes from an X-shaped image. When an image is now presented to the system, the total value (or some other statistic) of all the gates it passes can be taken as a compound estimate of the likelihood of its being an X. By introducing an element which performs this summation and compares the total to a fixed criterion, we have a network which will "decide" whether an image is an X or not on the basis of those likelihood estimates.

Network has Biological Characteristics

The mathematical analysis necessary to evaluate and optimize such a system is, of course, a large problem and is beyond the scope of this article. It is, however, pertinent to note that such a network would have the special characteristics attributed above to biological systems:

1. An image which did not occur during the training sequence would be "evaluated" in the same way as an image used in training. This assumes that the likelihood measures derived from the limited training sample were good estimates for the population of images.
2. There need be no unique paths in the system, and the memory of a trained identification has no single locus in the network.
3. The constraints imposed on the structure of the system may be very slight.

A basic perceptron network consists, then, of a retina of photocells, a parallel set of gates, called *association units*, which receive signals from the retina, and an evaluator unit with a 2-value output. An association unit is said to be *active* if it passes a retinal output. The "passing" actually consists of sending to the evaluator a signal equal to the value of that association unit. Feeding identification signals to the association units is called *reinforcement*. The evaluator and output unit is called a *response unit*.

For identification problems in which several different shapes of images are to be identified, a set of the basic perceptron mechanisms, as described in the preceding paragraph, can be arranged to act in parallel on the output from a single retina. In this way the 2-valued outputs of each of several similar perceptron networks can be combined to provide a multiple-valued output.

Network Capabilities Assessed

Work with the Mark I is aimed at exploring the characteristics of perceptron networks, and assessing their capabilities in relation to concrete problems.

One of the questions asked is: What is the practical capability for identification tasks of a perceptron of relatively modest size and with a very general and unconstrained connection scheme? To answer this question, a "random" connection scheme between the sensory and association units of the Mark I makes it possible for each association unit to receive inputs from a random "scatter" of points on the retina. The plan for the perceptron can thus be said to contain no information regarding the kind of images it must identify.

The Mark I perceptron was presented with the task of identifying the 26 letters of the alphabet. The letters used were from a standard font, and were "shown" to the perceptron by exposing them one at a time to a certain part of the retina. After sixteen training exposures to each letter, the perceptron was able to identify all the letters correctly.

A number of questions independent of the type of sensory-association unit connections employed have also been investigated. One of the most important of these questions is: What are the effects of different kinds of training procedures on the rate at which a

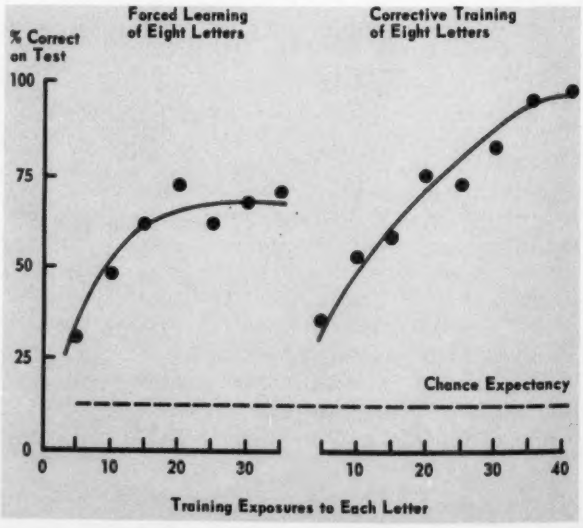
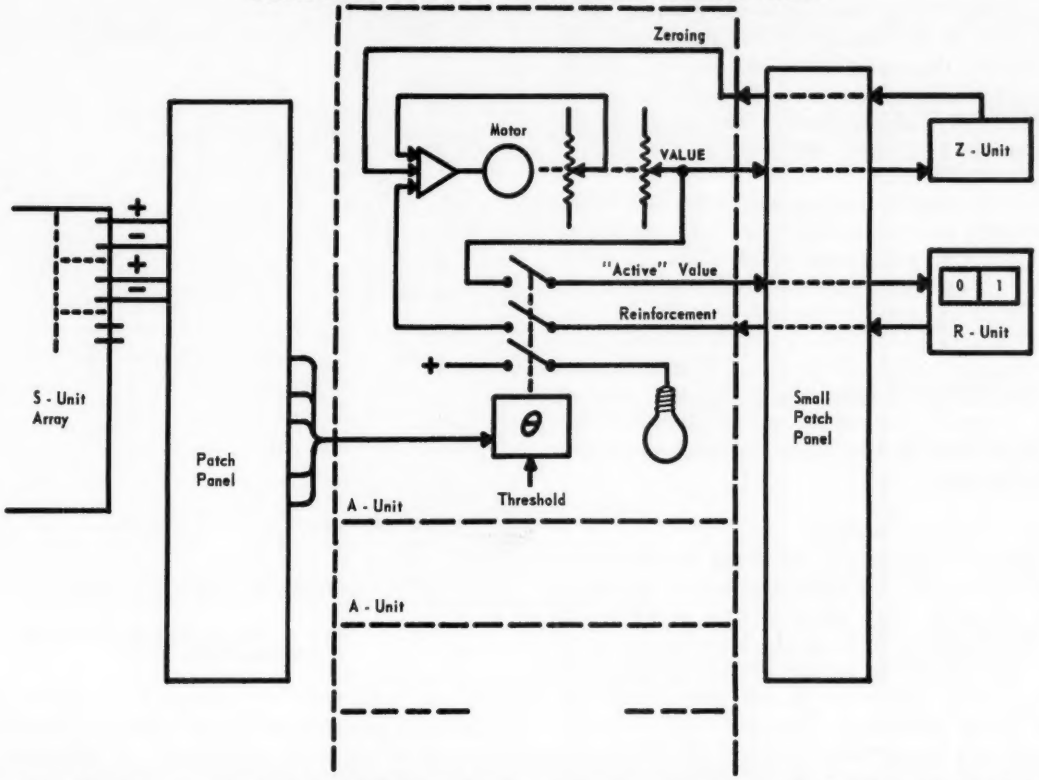


FIG. 1 — Learning Curves for Eight Letter Identification Task with Forced Learning and Error Correction Training Techniques.

*In this case "passed" implies an output drawn from a stored value rather than from a binary "1", "0" choice.

CONSTRUCTION OF THE MARK I PERCEPTRON



The Mark I perceptron was constructed to verify the mathematical predictions of perceptron operation, and to provide an experimental research tool for the study of further problems in pattern recognition. Construction was started following an investigation of available techniques that might be applied to the perceptron. In the interest of economy and expediency, electromechanical devices were used extensively throughout the system. In particular, the electromechanical integrators are employed for the "memory" of the system, since their long time constant cannot be matched within practical bounds of availability and price.

Figure illustrates the organization of the Mark I perceptron. The sensory devices (S-units) translate the stimulus pattern into a discrete set of electrical signals. The sensory device is a 20 x 20 square array of photo-resistive cells mounted in a phenolic base plate. This plate is mounted in the film plane of a view camera. The stimuli are white symbols held in front of the camera on a black background about 2 feet square.

The photocell currents actuate transistor-driven relays which supply the excitatory and inhibitory (plus and minus) S-unit output signals. Each photocell which receives sufficient light supplies both signal polarities to a large patch board. Since 20 output connections are made available for each signal from an S-unit and there are 400 S-units with bipolar outputs, the patch board has 400 x 20 x 2 or 16,000 available output connections.

The A-unit inputs are also transistor-driven relay circuits. The threshold is common to all A-units. When an A-unit becomes active, its relay closes and connects the A-unit value to the output; it connects the integrator and applies voltage to a lamp for visual indication of its activity.

The A-unit integrator consists of a d-c motor driving a potentiometer. The voltage at the potentiometer arm provides a measure of A-unit integral, or value. A second potentiometer on the same shaft provides a local feedback loop to allow decay of the A-unit value with time. Normally, the decay voltage is applied only during the resetting of the A-unit to its zero position for the start of tests.

Although the Mark I perceptron was constructed with 512 A-units, a larger number of A-units would give better results.

An R-unit is a two-state device consisting of a d-c amplifier driving a relay. The R-unit input signal is the sum of a set (the source set) of A-unit outputs. The R-unit provides a visual indication of its state (this is the perceptron output), and in addition, transmits a reinforcement signal to its source-set of A-units. Those A-units in the same source-set which are active integrate the reinforcement signal to increase their values. The A-units in the source-set which are not made active by that particular stimulus do not integrate the reinforcement signal.

There are eight R-units available in the Mark I perceptron. The A-units may all be connected to one R-unit but then only one output is available. On occasion, the perceptron may be subdivided into as many as eight smaller perceptrons when discrimination between several stimuli is desired. Such sub-division also permits comparison of several perceptrons all doing the same task.

perceptron learns a task, and on the ultimate level of proficiency achieved? Recent theoretical work has shown that a considerable difference can exist between the ultimate proficiences produced by the two methods of training termed *forced learning* and *error correction.*[2] This difference is demonstrated in a number of ways on the Mark I.

Correct Responses Reinforced

In forced learning, the correct identification response is reinforced every time the perceptron is shown an image. In the error correction technique, the correct response is reinforced only when the perceptron gives the wrong response.

One experiment compares the efficacy of these two training procedures for the task of identifying eight alphabetic letters. This task differs from the complete alphabet task in that the letters are not confined to a single fixed location on the retina, but are free to occur in a variety of locations.

The resulting learning curves (Fig. 1) show, for their respective training conditions, the rise in the number

of correct identifications observed on a test administered repeatedly during the course of training. The initial rise rates of the two curves is approximately the same. However, the curve for forced learning quickly levels off at a relative low level of performance — about 70%, or 57% above chance. The curve for the error correction technique continues to rise until it reaches the 100% level.

Although the forced learning technique is inferior to the corrective technique under the above conditions, it has an interesting advantage which might be incorporated in future, more sophisticated training techniques. Suppose an identification task is so difficult that the *trainer* of the perceptron is unable to make correct identifications 100% of the time. Would the perceptron then attain, at most, the proficiency level of its trainer, or could it exceed the trainer's performance? For the forced learning technique, the latter alternative is actually the case!

"Imperfect" Trainer Simulated

An "imperfect" trainer was simulated on what is, in fact, a very easy task: the discrimination of the letters E and X whenever they occur over a given retinal region. On a random 30% of the training exposures an error was introduced in the forced learning procedure; e.g., when shown an X, the identification response of E was reinforced. We reproduced this experiment on two independent halves of the Mark I, in order to obtain an estimate of the central tendency and variability of performance for perceptrons of this type (see Fig. 2).

Mistakes made during the training procedure reduce the date at which the learning curve rises (compare 2b with 2a), but the perceptron does actually exceed the performance of its trainer (dotted line in 2b). For this case, indeed, the terminal level of performance is identical to that resulting from errorless training. It is also

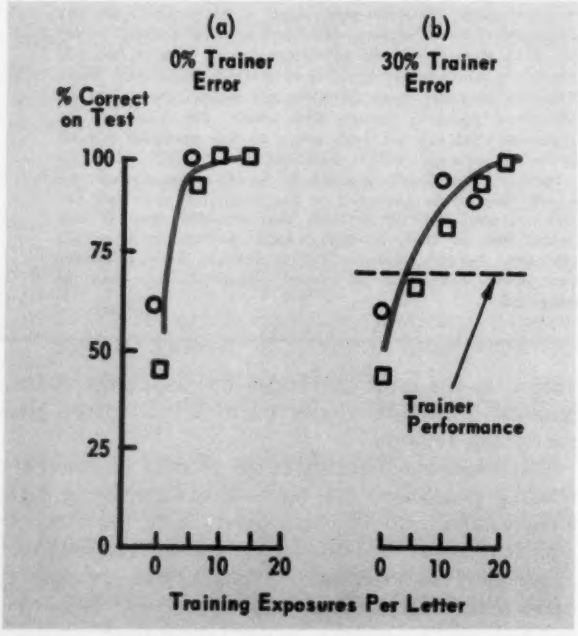


FIG. 2 — **Effect of Trainer Error on Learning of E-X Discrimination Task.**

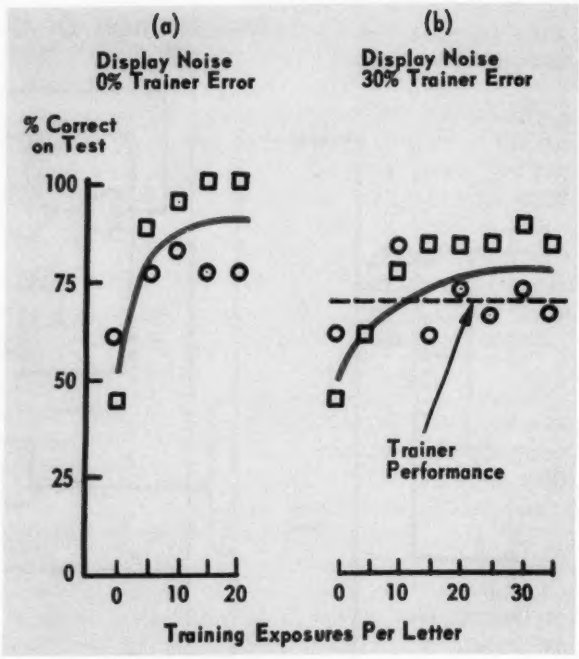


FIG. 3 — **Effect of Display Noise on Learning of E-X Discrimination Task.**

significant that the two independent halves of the Mark I (indicated by the square and the circular data points) show the same uniformity of performance in the two training conditions.

What is the effect of random "noise" in the optical display? In one experiment, employing the basic E-X discrimination task, a random pattern of spots was superimposed on each letter exposure (with a different random pattern on each exposure). Thus the perceptron was required to learn to discriminate between E and X, wherever they occurred in the prescribed retinal region, through a fairly high level of noise (see Fig. 3a).

Comparing Fig. 3a with Fig. 2a indicates that the introduction of noise results in a decreased maximum level of performance, and an increased variability in the performance of different perceptrons of the same type.

The conditions of an erroneous training program and a noisy display were combined in the experiment the results of which are shown in Fig. 3b. A slight decline from the errorless training of Fig. 3a is evident, but the central tendency of performance once again rises above the level of trainer accuracy.

Possible Applications of Future Perceptrons

It is possible to extrapolate some of the fundamental characteristics of perceptron systems observed in the Mark I to larger machines. Such machines might be capable of useful applications in many situations which now require human operators to differentiate between optical patterns.

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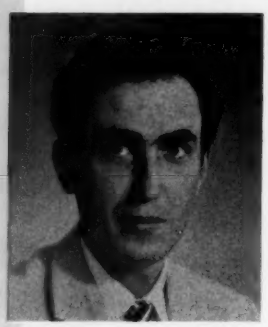

JOHN C. HAY, coauthor of "The Mark I Perceptron," and associate psychologist, has extended his interest in animal perception and learning to include the analogs of these phenomena to artificial systems. He has been applying some of the techniques of experimental psychology to the study of the perceptron for the past several months.

An instructor in experimental psychology at Oberlin College before joining the Laboratory, Mr. Hay received his bachelor's degree at Cornell University and his master's degree at Swarthmore. He is currently completing his thesis for a doctoral award from Cornell.

CHARLES W. WIGHTMAN is project engineer for developing the actual hardware for the Mark I perceptron.

A graduate of Renssalear Polytechnic Institute in electrical engineering, Mr. Wightman has participated in several programs involving missile guidance, servomechanisms and instrumentation, including work on analog and digital computers. Prior to his joining Cornell Aeronautical Laboratory as associate electronics engineer, Mr. Wightman served with the U.S. Army and worked as a test engineer for the General Electric Company.

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"THE PERCEPTRON: A PROBABILISTIC MODEL FOR INFORMATION STORAGE AND ORGANIZATION IN THE BRAIN," Rosenblatt, Frank; Reprinted from the Psychological Review, Vol. 65, No. 6; November 1958; 22 pages.

A description of some of the fundamental properties of perceptron networks, with comparisons to other theoretical cognitive systems and to the observed properties of biological cognitive systems.

"EFFECTS OF CONCENTRATED HYDROGEN PEROXIDE ON MECHANICAL AND CORROSION PROPERTIES OF STRUCTURAL ALUMINUM ALLOYS," Gillig, Franklin J.; CAL Report No. KC-1164-M-11; February 1959; 57 pages.

Nine wrought alloys and three cast alloys were selected for evaluation. The properties of the alloys were evaluated in the "as-received" condition and also as weldments. Stressed specimens were included to determine the possibility of stress corrosion effects. The specimens were exposed for a maximum of six months to 90% commercial hydrogen peroxide with and without added chlorides.

"SOME ASPECTS OF THE THERMAL DESIGN OF ELECTRONIC EQUIPMENT OPERATING AT 300-500°C ENVIRONMENTAL TEMPERATURE," Welsh, James P.; Reprinted from the IRE Transactions on Aeronautical & Navigational Electronics, Vol. ANE-5, No. 4, December 1958; 4 pages.

Aspects of electronic part-cooling techniques applicable to 300-500°C equipments are presented. Contrary to some beliefs, the minimization of thermal resistance at these temperatures is as important as at lower temperatures. The significant shifts in the natural modes of heat transfer which occur with high-temperature electronic parts are outlined, together with some recommended methods of cooling high-temperature parts and assemblies.

"A CONTROLLER DISPLAY TECHNIQUE FOR A TERMINAL AIR TRAFFIC CONTROL SYSTEM," Dufort, Robert H.; Sherard, George W.; Smith, Milton D.; CAL Report No. JA-1266-S-14; July 1959; 49 pages.

The feasibility of a possible terminal area traffic control display technique has been investigated. The technique has been based on the control doctrine, input-output information, and computer equipment available in the FAA/BRD Data Processing Central currently under development, in order that applicability to a real system could be examined.

"THE OCCURRENCE AND AVOIDANCE OF MID-AIR COLLISIONS," Deitchman, Seymour; Reprinted from Aero-Space Engineering, Vol. 18, No. 1; January 1959; 7 pages.

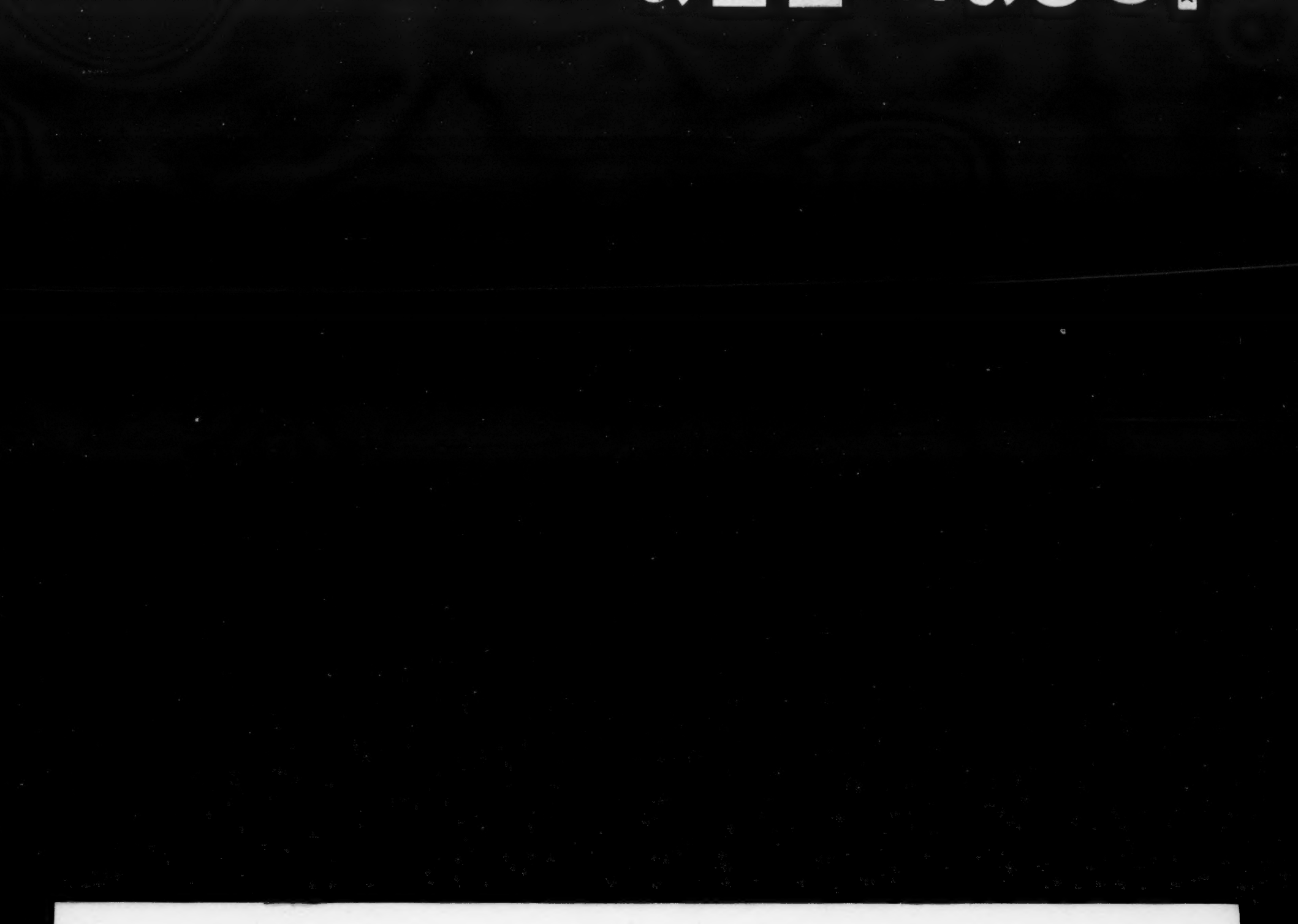
A simple air traffic model has been constructed and examined in conjunction with the physical requirements for anticipating and avoiding mid-air collisions. The analysis has indicated the kinds of aircraft that become involved in potential collision situations, where these situations may occur most frequently, and how their number may be reduced. The relative utility of various approaches to the problem of avoiding mid-air collisions through the use of airborne devices and systems has also been evaluated with the aid of data gained from the model.

"HYPERSONIC SHOCK-LAYER THEORY OF A YAWED CONE AND OTHER THREE-DIMENSIONAL POINTED BODIES," Cheng, Hsien K.; CAL Report No. AF-1270-A-1; September 1959; 69 pages.*

A detailed treatment of the problem of hypersonic flow over yawed circular cone has been made through application of the shock-layer approximation in conjunction with small perturbation in the yaw angle.

"CONDENSATION NUCLEI EXPERIMENTS WITH SIMPLE APPARATUS," Jiusto, James E. and Pilié, Roland J.; Reprinted from Weatherwise, Vol. 11, No. 6; December 1958; 3 pages.

This article presents a description of simple apparatus that can be readily duplicated by the student meteorologist for close-up observation of the condensation phenomenon or by the research physicist for obtaining reproducible nuclei measurements.

"GRAPHICAL COMPUTATION OF SHOCK AND DETONATION WAVES IN REAL GASES," Markstein, George H.; Reprinted from the American Rocket Society Journal, Vol. 29, No. 8; August 1959; 3 pages.

The conservation relations across a shock or detonation wave are represented in the form of a graph applicable to real gases of arbitrary composition. Computation of shock waves reflected from a closed end is performed by means of another universally applicable graph.